

US006895278B1

(12) **United States Patent**
Gordon

(10) **Patent No.:** **US 6,895,278 B1**
(45) **Date of Patent:** **May 17, 2005**

(54) **GASTRIC STIMULATOR APPARATUS AND METHOD FOR USE**

(75) Inventor: **Pat L. Gordon**, Wyzata, MN (US)

(73) Assignee: **Transneuronix, Inc.**, Mt. Arlington, NJ (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/466,387**

(22) Filed: **Dec. 17, 1999**

Related U.S. Application Data

(60) Provisional application No. 60/129,209, filed on Apr. 14, 1999.

(51) **Int. Cl.**⁷ **A61N 1/36**

(52) **U.S. Cl.** **607/40; 607/62**

(58) **Field of Search** 607/40, 45, 133, 607/8, 62, 58; 600/547

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,379,462 A	4/1983	Borkan et al.	607/117
4,459,989 A	7/1984	Borkan	607/60
4,612,934 A	9/1986	Borkan	607/62
4,719,922 A *	1/1988	Padjen et al.	607/62
4,793,353 A	12/1988	Borkan	607/60
5,222,494 A *	6/1993	Baker, Jr.	607/118
5,292,344 A	3/1994	Douglas	607/40
5,423,872 A	6/1995	Cigaina	607/40
5,607,459 A	3/1997	Paul et al.	607/29
5,690,691 A	11/1997	Chen et al.	607/40
5,836,994 A	11/1998	Bourgeois	607/40
5,861,014 A	1/1999	Familoni	607/40
5,995,872 A	11/1999	Bourgeois	607/40

FOREIGN PATENT DOCUMENTS

EP	0 626 181 A1	11/1994	A61N/1/362
WO	WO 97/31679 A2	4/1997	A61N/1/36
WO	WO 99/03532	1/1999	A61N/1/36

OTHER PUBLICATIONS

B. Bellahsene, et al., "Evaluation of a Portable Gastric Stimulator," *Proceedings of the Ninth Annual Conference of the IEEE Engineering in Medicine and Biology Society*, Nov. 1987, pp. 1652-1653.

(Continued)

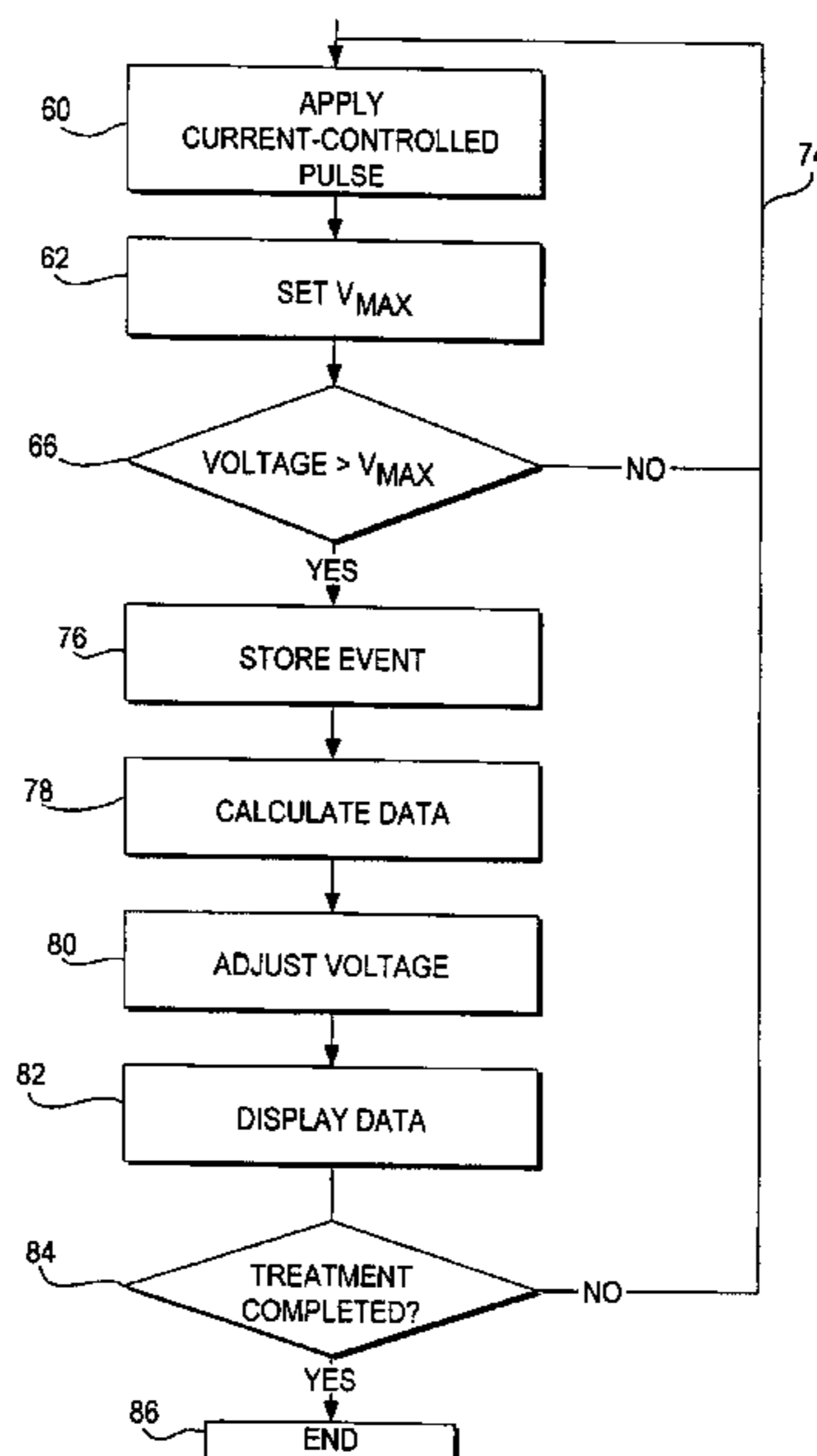
Primary Examiner—Kennedy Schaezle

(74) *Attorney, Agent, or Firm*—Fitch, Even, Tabin & Flannery

(57) **ABSTRACT**

Apparatus and method for stimulating neuromuscular tissue in the stomach. The neuromuscular stimulator stimulates the neuromuscular tissue by applying current-controlled electrical pulses. A voltage sensor detects the voltage across the neuromuscular tissue to determine if the voltage meets a predetermined voltage threshold. A control circuit adjusts the current-controlled pulse if the voltage is found to meet the voltage threshold, such that the voltage does not exceed the voltage threshold. A voltage-controlled pulse may also be applied to the tissue. A current sensor would then detect whether the current on the neuromuscular tissue meets a predetermined current threshold, and a control circuit adjusts the voltage controlled pulse such that the current does not exceed the current threshold. A real time clock may be provided which supplies data corresponding to the time of day during the treatment period. A programmable calendar stores parameters of the stimulating pulse, wherein the parameters have a reference to the time of day.

32 Claims, 9 Drawing Sheets



OTHER PUBLICATIONS

B. Bellahsene, "Effects of Gastric Electrical Stimulation (Pacing) as Measured Through Gastric Emptying and Electrogastrograms," *Dissertation Abstracts International*, vol. 50/02-B, 1988, p. 658.

J.D. Chen, et al., "Long-Term Gastric Pacing with a Portable Gastric Pacemaker to Aid Gastric Emptying in Humans," *Proceedings of the 1995 IEEE Engineering in Medicine and Biology 17th Annual Conference*, Sep. 1995, pp. 1691-1692.

J.D. Chen, et al., "Gastric Electrical Stimulation in Patients with Gastroparesis," *Journal of Gastroenterology and Hepatology, Proceedings of the Alimentary Disease Week*, Dec. 1997, pp. S232-S236.

S.D. Jundler, "An Electronic Pacemaker for the Electrical Control Activity of the Stomach," *Masters Thesis, Institute of Biomedical Engineering, University of Toronto*, Mar. 1991.

K.A. Kelly, "Differential Responses of the Canine Gastric Corpus and Antrum to Electrical Stimulation," *American Journal of Physiology*, vol. 226, No. 1, Jan. 1974, pp. 230-234.

L.J. Levien, "The Response of the Canine Stomach to Stimulatory and Inhibitory Vagal Nerve Activity," *Dissertation Abstracts International*, vol. 41/08-B, 1980, p. 2915.

M. Mintchev, et al., "Computer Model of Gastric Electrical Stimulation," *Annals of Biomedical Engineering*, vol. 25, No. 4, 1997, pp. 726-730.

S. Xue, et al., "Electrical Slow Wave Activity of the Cat Stomach: Its Frequency Gradient and the Effect of Indomethacin," *Neurogastroenterology and Motility*, vol. 7, No. 3, Sep. 1995, pp. 157-167.

N.B. Halpern, et al., "Effects of Partitioning Operations on the Electrical Activity of the Human Stomach," *Journal of Surgical Research*, vol. 32, No. 3, Mar. 1982, pp. 275-282.

R.L. Telander, et al., "Human Gastric Atony with Tachygastria and Gastric Retention," *Gastroenterology*, vol. 75, No. 3, Sep. 1978, pp. 497-501.

"Research at the Center for Semicustom Integrated Systems", University of Virginia, Internet website: <http://csis.ee.virginia.edu/research.html>, Jun. 5, 1998.

* cited by examiner

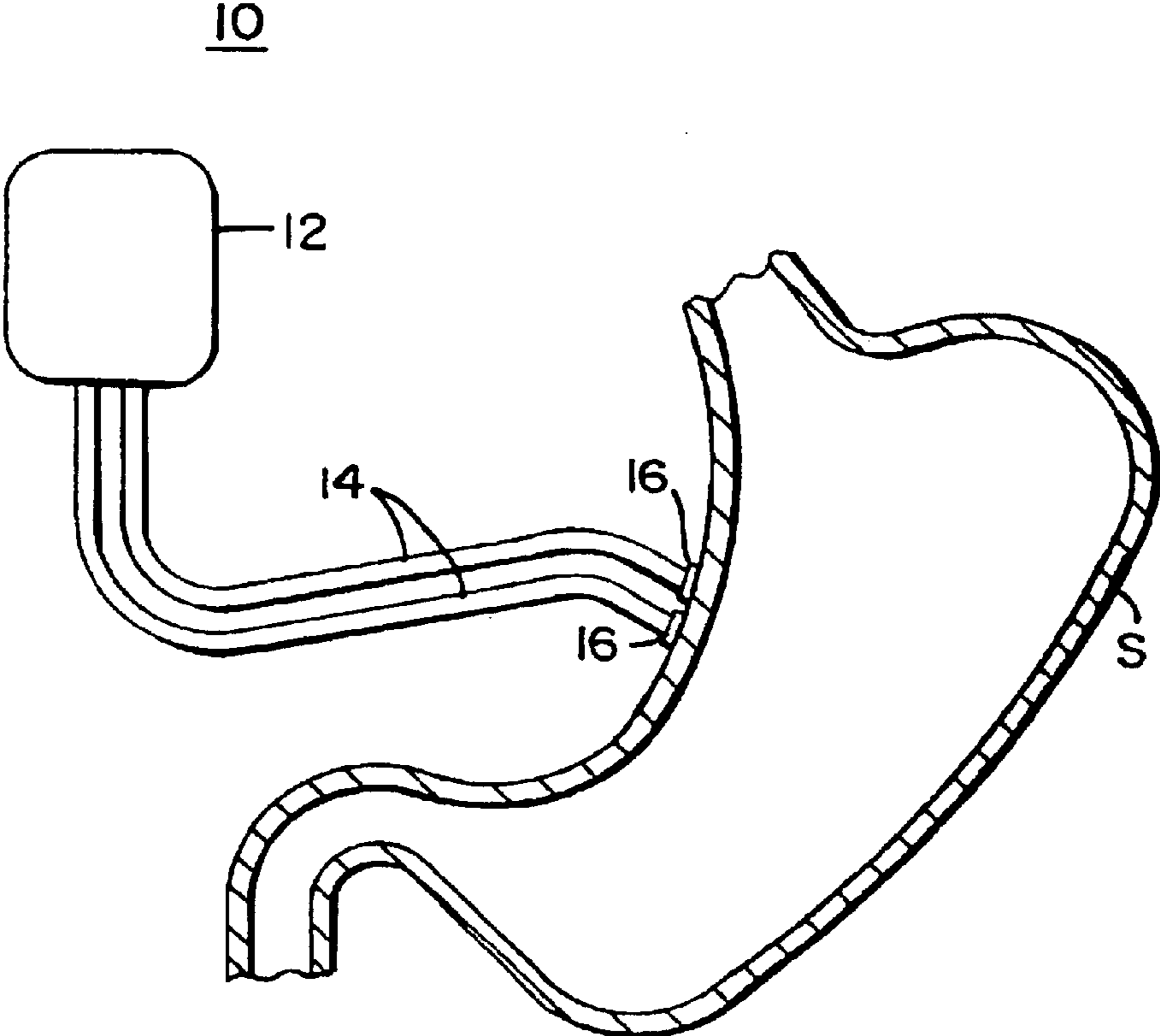
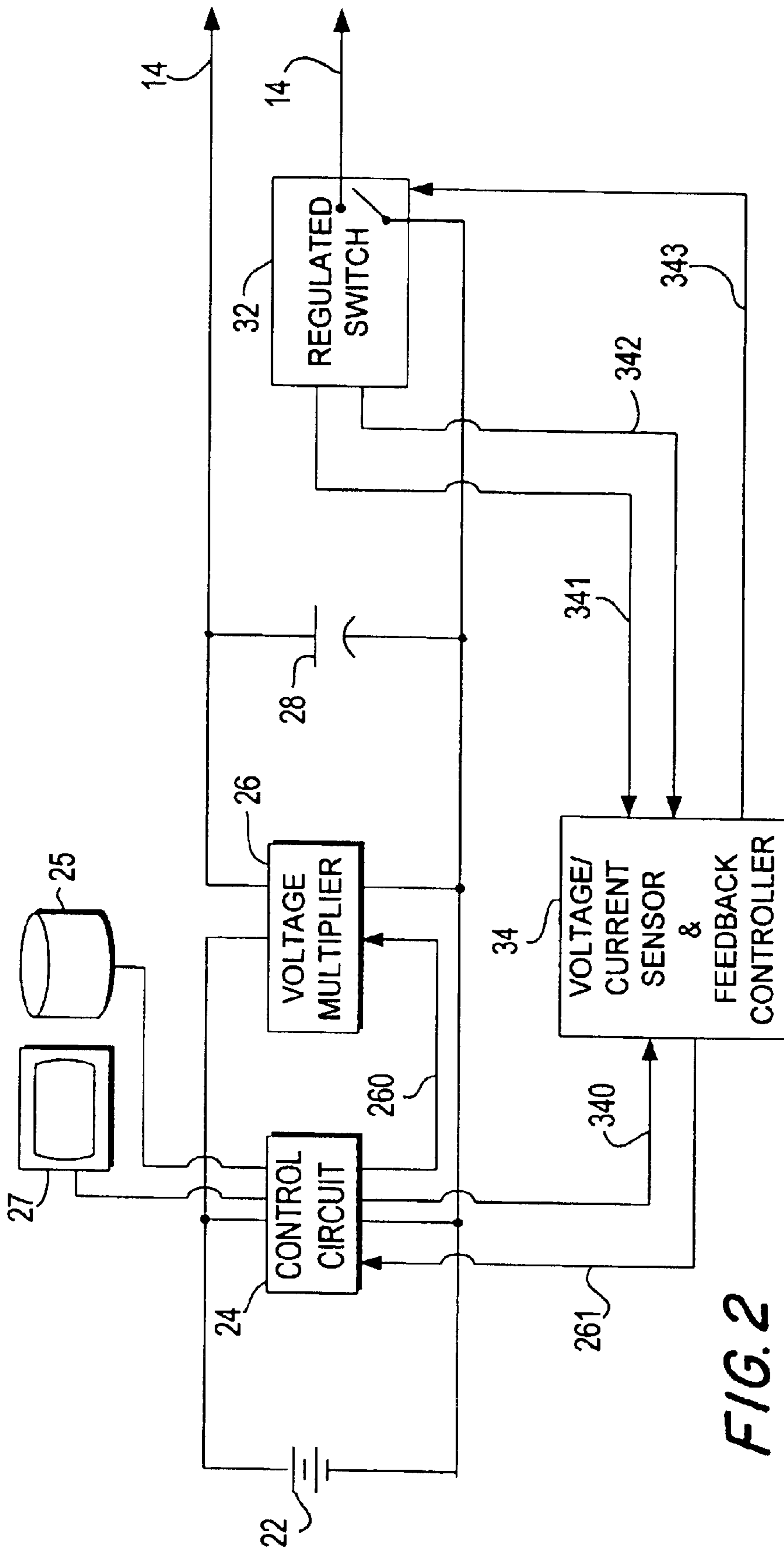


FIG. 1



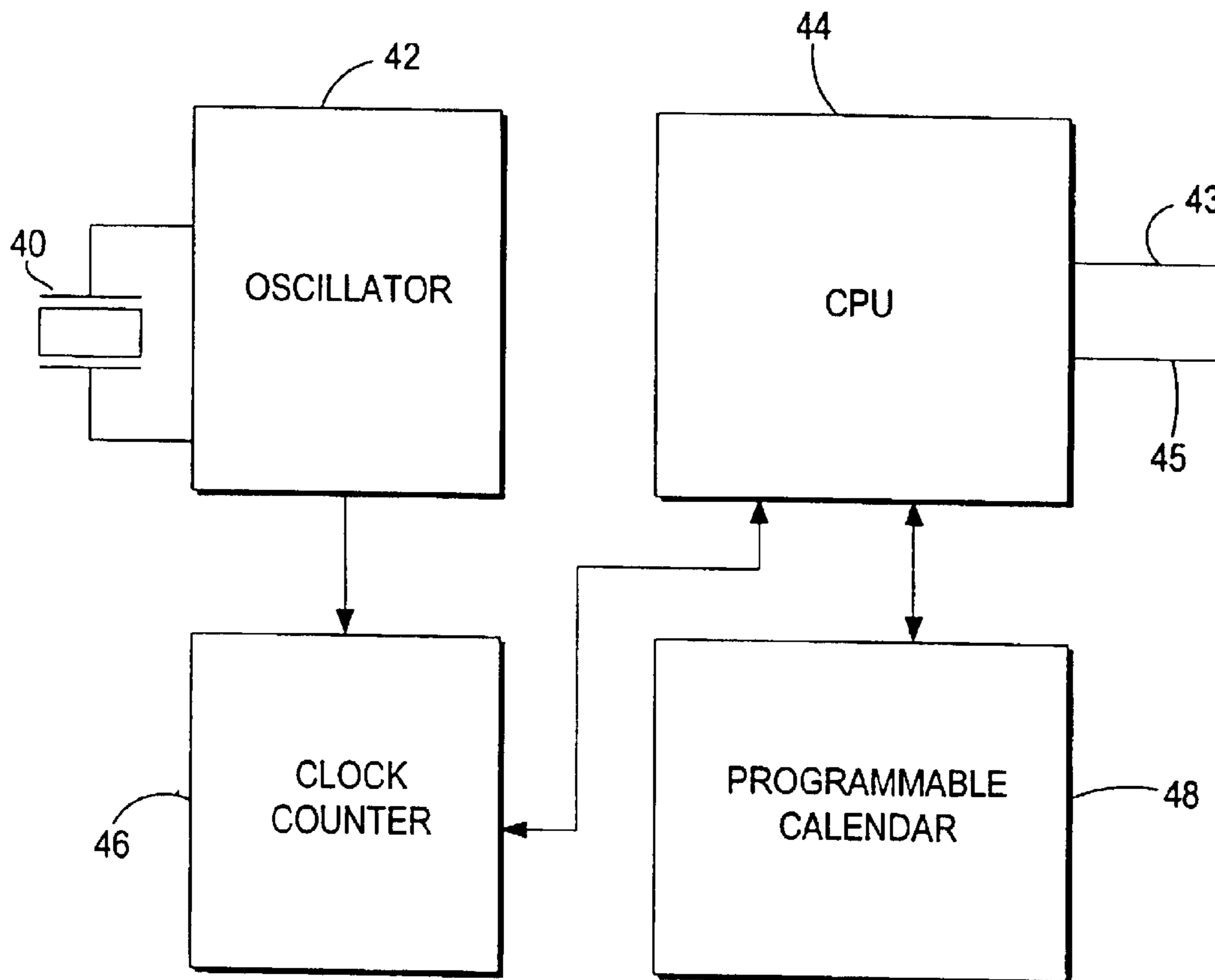


FIG. 3

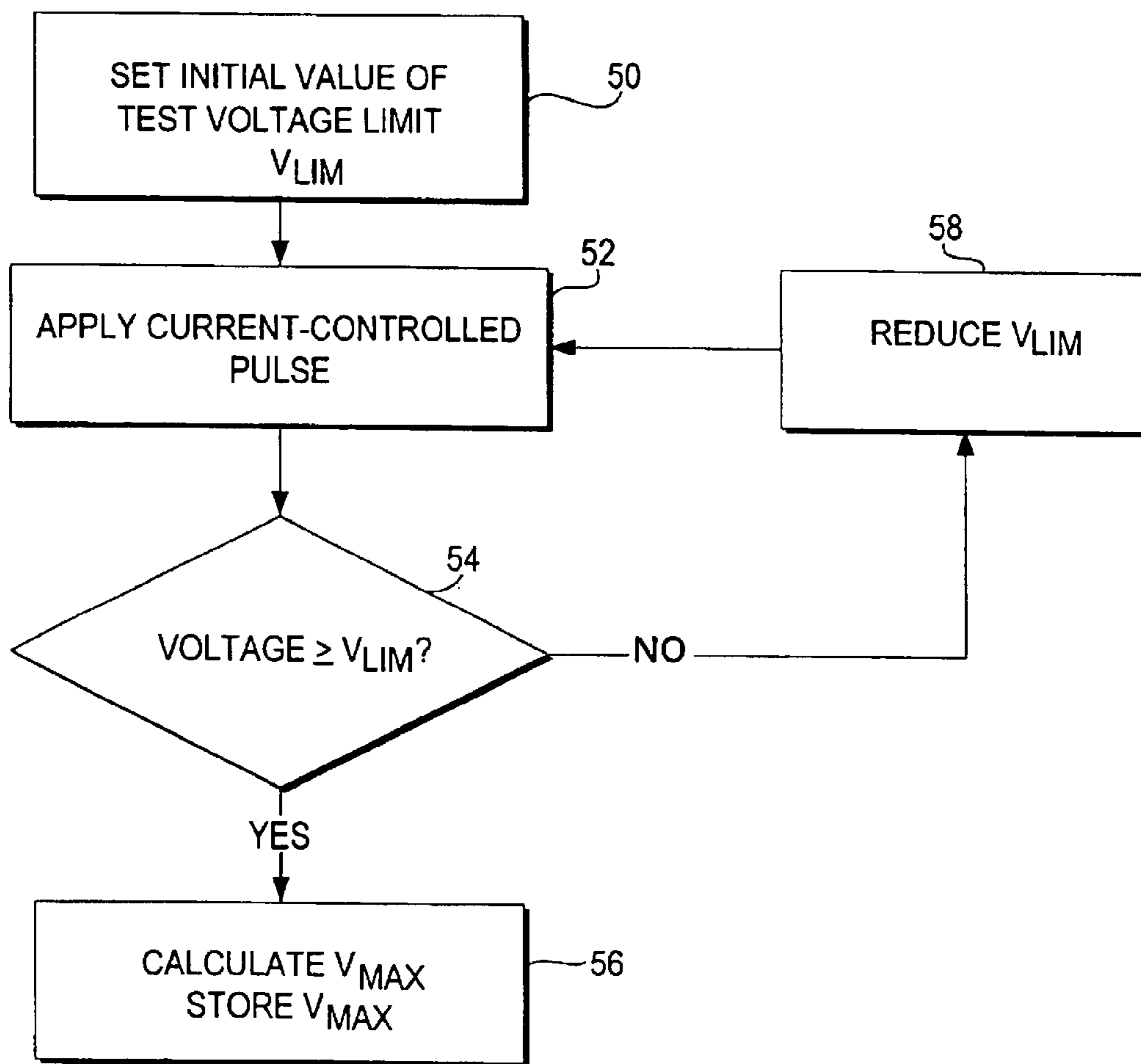
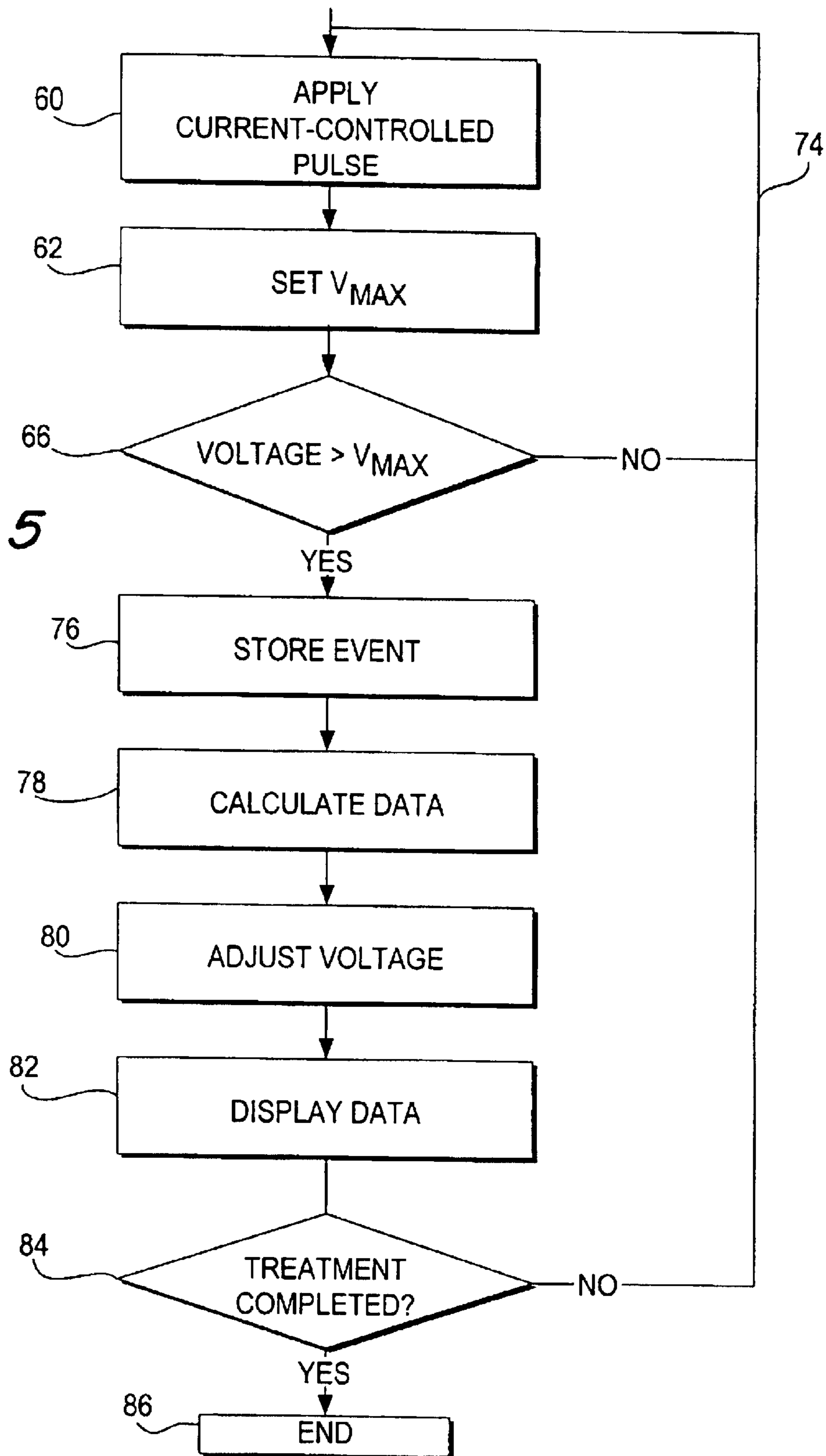
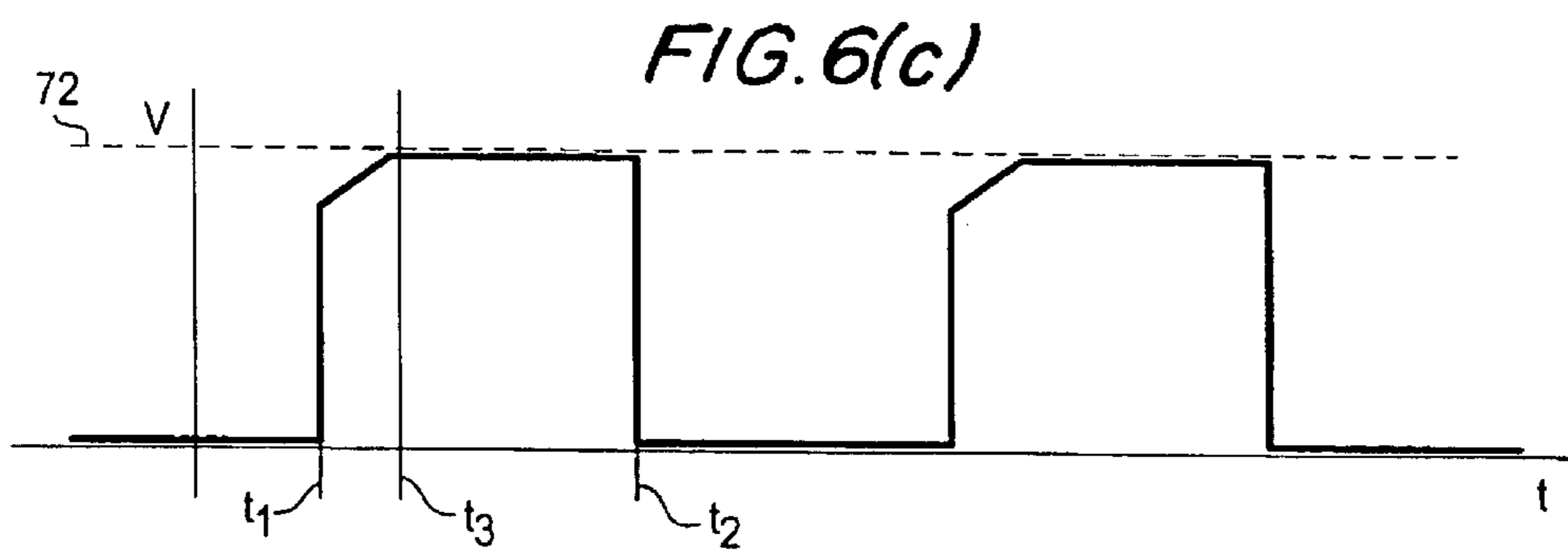
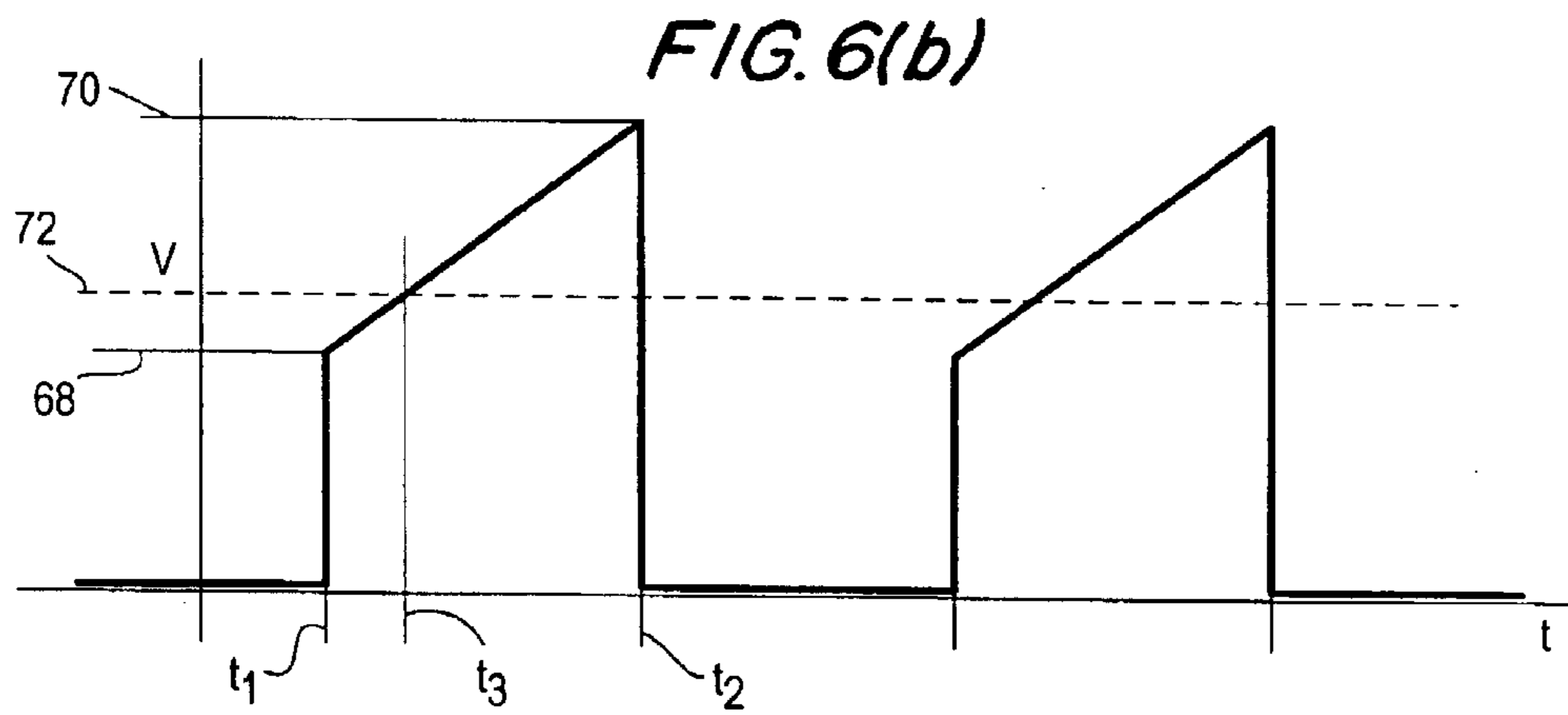
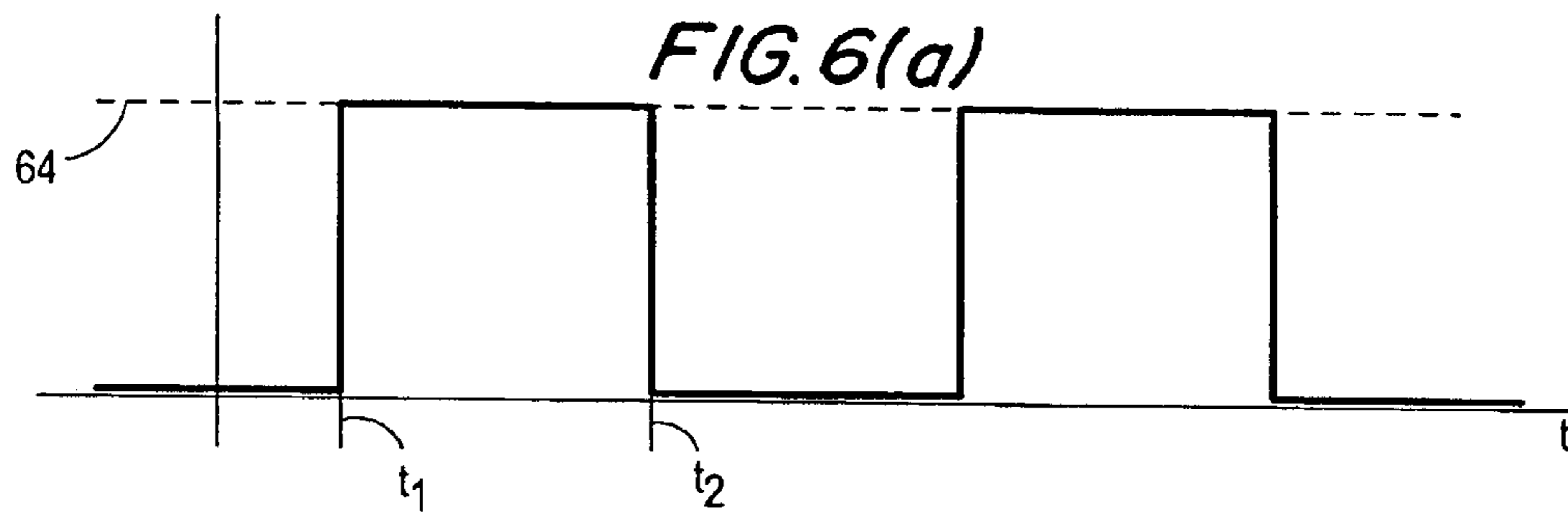


FIG. 4

FIG. 5





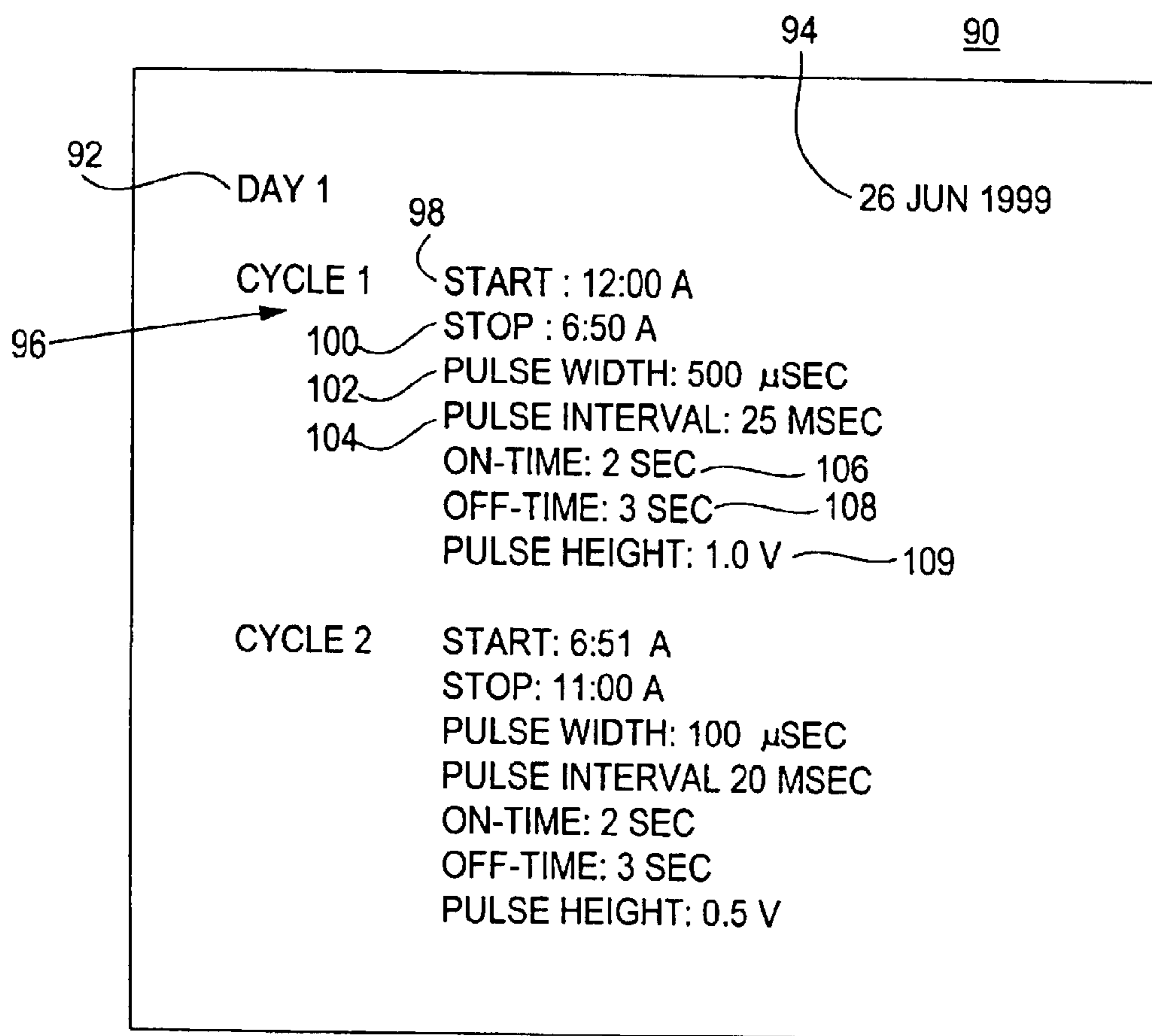


FIG. 7

FIG. 8

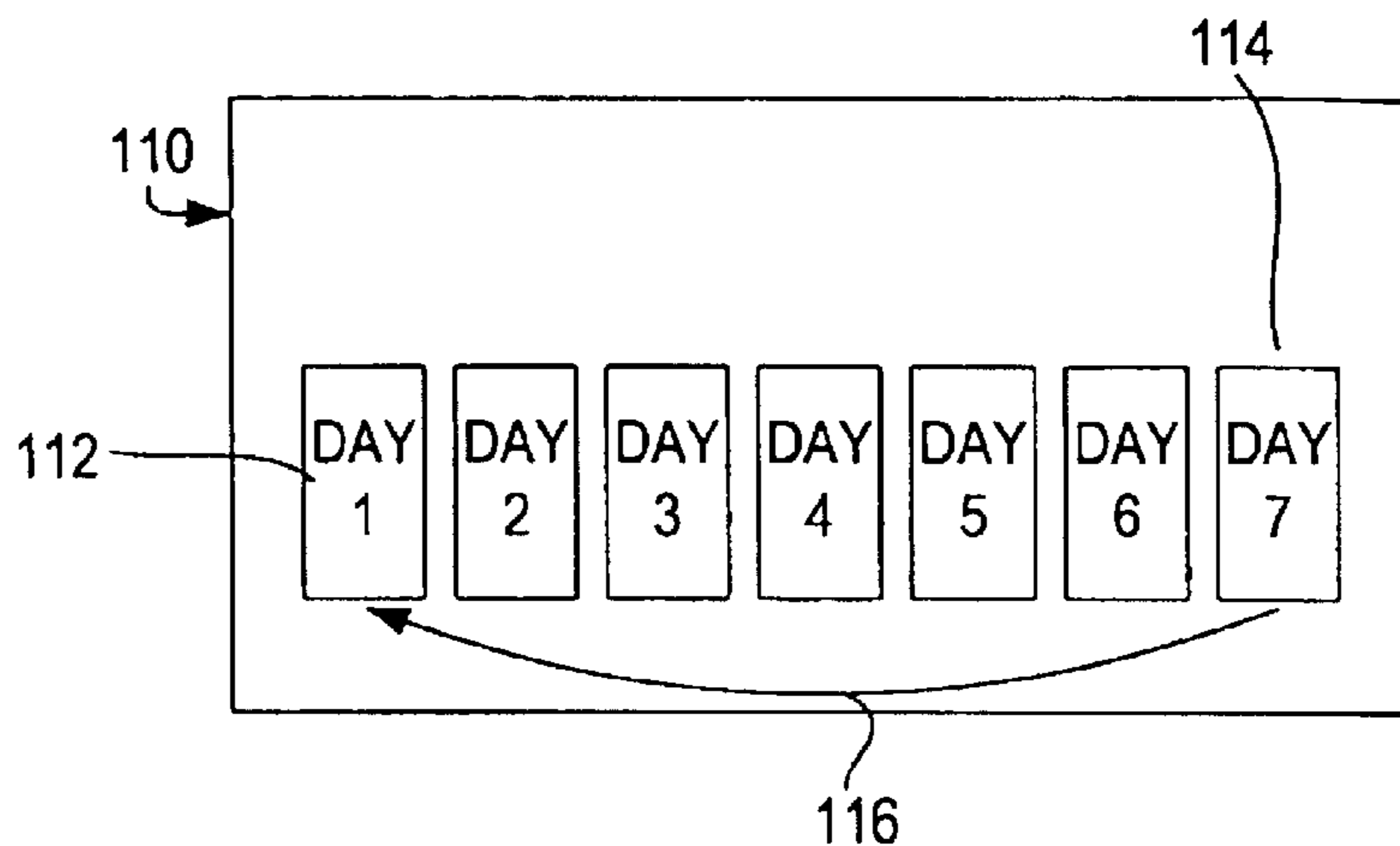
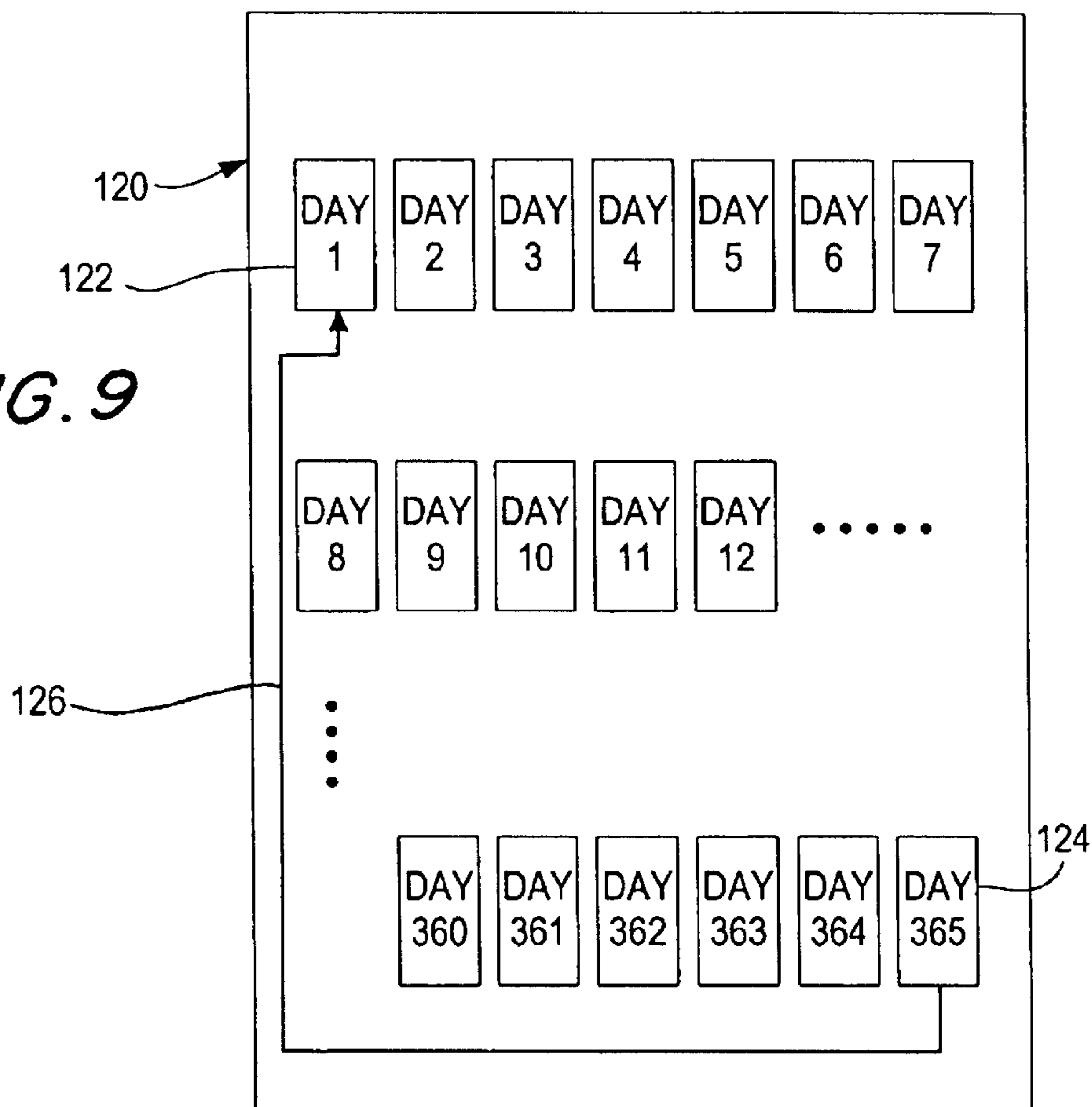


FIG. 9



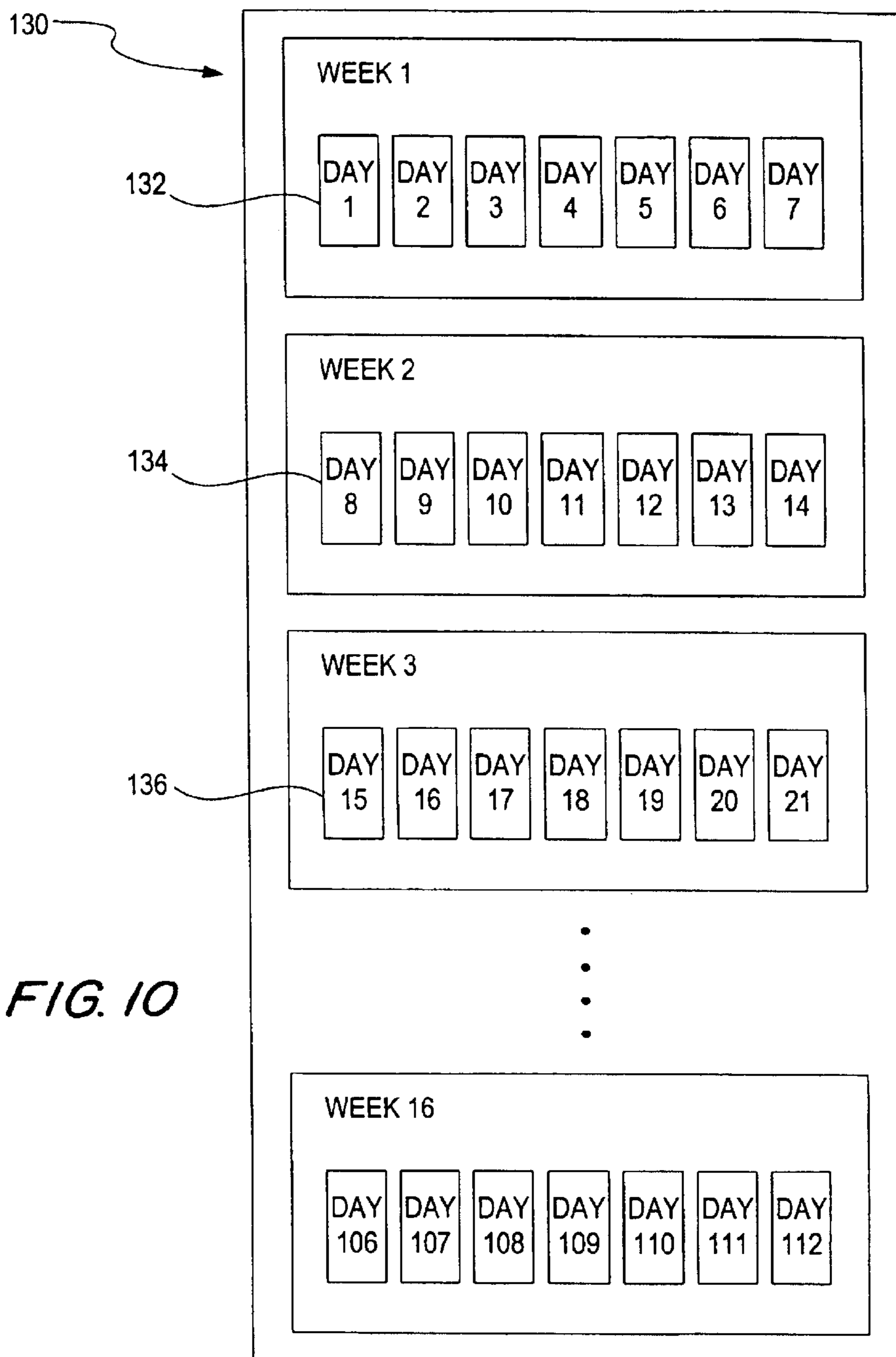


FIG. 10

GASTRIC STIMULATOR APPARATUS AND METHOD FOR USE

This application claims the benefit of U.S. Provisional application Ser. No. 60/129,209, filed Apr. 14, 1999, which is incorporated by reference in its entirety herein.

BACKGROUND OF THE INVENTION

This invention relates to electrical stimulation apparatus and methods for use in stimulating body organs, and more particularly to implantable apparatus and methods for periodic electrical gastric stimulation.

The field of electrical tissue stimulation has recently been expanded to include devices which electrically stimulate the stomach with electrodes implanted in the tissue. These gastric stimulators have been found to successfully combat obesity in certain studies. Medical understanding as to how this treatment functions to reduce obesity is currently incomplete. However, patients successfully treated report achieving normal cycles of hunger and satiation.

An apparatus and treatment method for implementing this therapy was described in U.S. Pat. No. 5,423,872 to Dr. Valerio Cigaina, which is hereby incorporated by reference in its entirety herein. The apparatus described in the Cigaina patent stimulates the stomach antrum pyloricum with trains of stimulating pulses during an interval of about two seconds followed by an "off" interval of about three seconds.

Current pacemaker design incorporates a number of features useful for the type of tissue or organ being stimulated. Pacemakers stimulating cardiac or neurological tissue, for example, may typically contain an accurate, drift-free crystal oscillator to carry out real-time functions such as pulse generation. In particular, some cardiac pacemakers use a time reference to keep track of the time-of-day with a 24-hour clock in order to log data or to vary pacing parameters during the 24-hour cycle. Similarly, neurological stimulators, such as a neurological stimulator manufactured by Cyberonics, may use the time-of-day as a reference to deliver one or more periods of pulse-train stimulation (typically lasting a few minutes each) to the vagus nerve to treat epilepsy.

The design and operation constraints for a gastric pacemaker, or stimulator, are substantially different from those for a cardiac pacemaker or a neurological pacemaker, for example. With a gastric stimulator for weight loss, size is less of a concern because of the large anatomy associated with obesity. However, a long operating life for an implantable device remains an important feature, given the significantly higher current drain required by this therapy compared to cardiac pacing. Since the implantable pulse generator may be located subcutaneously in the abdominal wall, it is feasible to use a larger device, including a larger, longer-life battery.

Moreover, stomach stimulation may require different levels and cycles of stimulation than that required for cardiac stimulation or nerve stimulation. In a neuromuscular stomach generator, for example, power consumption can be five to seven times higher than for a cardiac pacemaker. Maintaining the proper energy level for stimulation may place energy demands on the life of the battery. The characteristics of entrainment of the stomach tissue may require cycling of the electrical stimulation in more complex schedules than that previously required. Observations of early human implants have shown a surprising increase in the impedance of the electrode tissue interface, from about 700 ohms at time of implant to 1300 ohms after only as much as three

months of implants. With constant current and increased impedance, voltage drain on the battery may be unacceptably high.

Thus, there is a need to optimize the operation of gastric pacemakers, or stimulators, so as to provide a longer life for the device, and hence, a longer duration of therapy without the need for repeated surgical procedures.

It is an advantage to provide an apparatus and method of stimulation wherein voltage or current can be controlled to extend the useful life of a battery used therein.

It is also an advantage of the invention to provide an apparatus and method of stimulation that is able to calculate and store data parameters to improve the levels of stimulation based on operating conditions.

It is a further advantage of the invention to provide a clock function which allows the stimulation cycles of the tissue to be programmed and executed on long term basis.

SUMMARY OF THE INVENTION

These and other advantages of the invention are accomplished by providing apparatus and methods for stimulating neuromuscular tissue of the gastrointestinal tract by applying an electrical pulse to the neuromuscular tissue. The electrical pulse applied to the tissue may be a current-controlled pulse or a voltage-controlled pulse as deemed appropriate by one skilled in the art. In the case of a stimulator applying a current-controlled pulse, the stimulator may include a voltage sensor to sense the voltage across the neuromuscular tissue being stimulated. A voltage threshold is determined by the circuitry. In a preferred embodiment, the voltage threshold may be, adjustable and may be a function of the level of current applied to the tissue being stimulated.

The circuitry compares the sensed voltage and the predetermined voltage threshold. If the sensed voltage is found to meet or to exceed the predetermined voltage threshold, the circuitry will adjust the current-controlled pulse such that the sensed voltage does not exceed the predetermined voltage threshold. In a preferred embodiment, this may be accomplished by generating an error signal between the sensed voltage and the voltage threshold by using negative feedback control. The occurrence of the sensed voltage meeting or exceeding the predetermined voltage threshold may be stored as an "event", along with time at which the event occurred during the pulse interval and/or during the treatment period.

The circuitry also provides the capability of utilizing the data that is obtained during the sensing and feedback functions. For example, the total impedance may be calculated from the voltage and current values. One component of the impedance may be the electrode resistance, and the second component may be the polarization capacitance. The electrode resistance may be obtained by dividing the voltage by the controlled current. The capacitance may be obtained from the current divided by the time rate of change of the voltage. The calculated values of the resistance and the capacitance may be stored on a memory device or displayed on a display device, or used in the feedback process to determine the increment of adjustment to the current-controlled pulse.

The neuromuscular stimulator may also include a real time clock and a programmable calendar for tailoring the stimulating waveform parameters over the treatment period. The real time clock supplies data corresponding to the time of day during the treatment period. The programmable calendar stores parameters which refer to the shape of the

stimulating waveform. Each of the parameters may be referenced directly or indirectly to the time of day. Circuitry, such as a, control circuit, applies the stimulating pulses which are defined by the parameters at the appropriate times of the day during the treatment period.

In a preferred embodiment, the parameter may be a time period during which the electrical pulses are applied. The time period may be defined by a start time and a duration. When the time period is so defined, the circuit may apply the stimulating pulse beginning at the start time and continuing for the specified duration. The time period may alternatively be defined by a start time and a stop time. In such a case, the circuit applies the stimulating pulse beginning at the start time, and continues to apply the pulses until the stop time. According to another embodiment, the time period may be defined by a start time, a first duration with respect to the start time, and a second duration with respect to the first duration. The circuit may apply the stimulating pulse beginning at the start time and continuing for the first duration, and subsequently discontinuing the pulses during the second duration. Additional parameters may be a time period corresponding to the pulse width for each pulse during the series of electrical pulses, and a time period corresponding to the pulse interval between each pulse. A parameter may also include a voltage corresponding to the pulse height for each pulse in the series of electrical pulses.

The real time clock and the programmable calendar allow the stimulating waveform to vary over greater periods of time. For example, the real time clock may supply data corresponding to a week during the time period. Consequently, the waveform may be programmed to apply a different waveform during each particular week in the treatment period. The real time clock may also supply data corresponding to the day of the week during the treatment period. Alternatively, the real time clock may supply data corresponding to a month of the year during the treatment period, such that the waveform may vary from month-to-month as the treatment progresses. Moreover, the real time clock may also supply data corresponding to the day of the month, and/or the day of the year.

Although current-controlled stimulating pulses are described above, the invention is equally applicable to constant voltage and voltage-controlled pulses.

Further features of the invention, its nature and various advantages will be more apparent from the accompanying drawings and the following detailed description of the preferred embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a simplified view of a preferred embodiment in accordance with the invention.

FIG. 2 is a simplified schematic view of a component of the apparatus of FIG. 2 in accordance with the invention.

FIG. 3 is a simplified schematic view of a component of the apparatus of FIG. 3 in accordance with the invention.

FIG. 4 is a flow chart of steps involved in creating a table of voltage threshold values and associated current values in accordance with the invention.

FIG. 5 is a flow chart of steps involved in comparing sensed voltage values with voltage threshold values in accordance with the invention.

FIG. 6(a) is a time plot illustrating a current wave form in accordance with the invention.

FIG. 6(b) is a time plot illustrating a prior art voltage wave form corresponding to the time plot of FIG. 6(a).

FIG. 6(c) is a time plot illustrating a voltage wave form corresponding to the time plot of FIG. 6(a) in accordance with the invention.

FIG. 7 illustrates a data structure for storing parameters for the waveform of a stimulating pulse in accordance with the invention.

FIG. 8 illustrates another data structure in accordance with the invention.

FIG. 9 illustrates yet another data structure in accordance with the invention.

FIG. 10 illustrates another data structure in accordance with the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

An improved neuromuscular stimulator is illustrated in FIG. 1, and designated generally with reference number 10. The stimulator 10 includes an implantable pulse generator 12, a lead system 14 of one or more electrodes 16. Stimulator 10 may use voltage, controlled and/or current controlled stimulation in such a way to limit power drains from the battery and to allow accurate determination of total impedance, including lead resistance and polarization capacitance. Consequently, maintaining substantially consistent levels of power consumption may dramatically improve longevity. Stimulator 10 may limit changes in power consumption and may store data, which may be provided to the clinician or used to vary stimulation parameters. For example, stored data may include the occurrences of a voltage and/or current limitation, during a stimulation pulse. Measured parameters may be stored to correlate stimulation levels with operating conditions in order to maintain consistent power consumption, as will be described in greater detail hereinbelow.

The implantable pulse generator 12 provides a series of electrical pulses to the stomach S. The implantable pulse generator 12 may be surgically implanted subcutaneously in the abdominal wall. The electrodes 16 may be installed in contact with the tissue of the stomach. Electrodes may be positioned on the outer surface of the stomach, implanted within the stomach wall, or positioned on the inner surface of the stomach wall. For example, the electrodes may be attached to the tissue by an electrocatheter as described in U.S. Pat. No. 5,423,872 to Cigaina patent 5,423,872, incorporated by reference above. Alternatively, the electrodes may be as described in copending U.S. Application PCT/US98/1042 filed on May 21, 1998, and copending application 09/122,832, filed Jul. 27, 1998, both of which are incorporated by reference in their entirety herein. As yet another alternative, electrodes may be substantially as described in U.S. Pat. No. 6,606,523 to Jenkins and U.S. Pat. No. 6,542,776 to Gordon et al., both of which are incorporated by reference in their entirety herein.

A preferred embodiment of a current-controlled and/or voltage-controlled stimulator circuit according to the present invention is illustrated in FIG. 2, and hereinafter referred to as I/V circuit 20. I/V circuit 20 may typically be housed in implantable pulse generator 12. I/V circuit 20 may limit power drains from the battery 22 and allow accurate determination of total impedance, including lead resistance and polarization capacitance.

The I/V circuit 20 also includes a control circuit 24, a voltage multiplier 26, storage capacitor 28, a regulated switch 32, and a voltage and/or current sensor and feedback controller 34 to regulate switch 32. The stomach tissue stimulation occurs on leads 14, which are in turn connected

to electrodes 16 (FIG. 1). Moreover, memory 25 may be provided to store data, and display unit 27 for displaying data may be provided.

The battery 22 may be selected in order to have long life characteristics when implanted in the patient. The voltage-control and current-control features of the invention may extend battery life further. Preferably, the battery 22 has deliverable capacity of greater than 2.5 amp-hours. In a preferred embodiment, two batteries may be provided.

The regulated switch 32 is designed to control current and/or voltage levels either throughout the entire output stimulator pulse, e.g., by using continuous feedback, or only at the leading edge, e.g., by selecting the appropriate initial voltage on capacitor 28 based on $V_C = V_{control}$ or $V_C = I_{control} \cdot R_{electrode}$.

The shape of the current and/or voltage waveform applied to the stomach tissue is adjustable and controlled by digital means in the control circuit 24, which typically is or contains a microprocessor.

The timing features of control circuit 24 are illustrated in FIG. 3. By using a crystal 40 to control oscillator 42 (which is either internal or external of processor 44 which may receive input 43 from control circuit 24 or provide output 45), accuracy is achieved for real-time clock counter 46. Alternatively, the oscillator 40 and count down chain can also be external to processor 44 and also be used to generate the stimulating waveform. Typically, a 32 or 100 kilohertz crystal clock may be used to provide timing. Stimulation pulse width is typically 100 to 500 microseconds (10 to 50 oscillations of 100 kilohertz clock), and the pulse interval may be 25 milliseconds or 2500 oscillations. The "on time," i.e., the period in which the pulses are applied, may be two seconds (200,000 oscillations) for this waveform, and the "off time," i.e., the period in which no pulses are applied, may be three seconds. It is useful to synchronize time inside the processor 44. A programmable storage device, such as programmable calendar 48, may be used to keep track of different times during the treatment period, such as hours of the day, day of the week, etc.

With continued reference to FIG. 2, the electrodes 16 (FIG. 1) present an impedance to the stimulating output leads 14 of I/V circuit 20. This impedance may be made up of two components. The first component is a resistance due to net energy transfer from circuit 20 to the stimulated tissue S, and the second component is a capacitance in series with the resistance due to ion transfer and charge accumulation across the electrode-tissue interface. FIGS. 6(a)-(c) illustrate the effects of these components. If a pulse of constant current is sent through electrodes 16, as illustrated in FIG. 6(a), the resistance component causes a voltage to immediately appear across the electrodes (FIG. 6(b)). As the current continues to flow during the pulse, the capacitance component charges up, which may contribute to a steady increase, in voltage during the pulse. Both of these components may vary in value from patient to patient. For an individual patient, these values may also change after implantation due to factors such as, for example, location of electrode placement, shifts in placement, changes in physiological conditions at the tissue interface, changes in anatomical shape, etc.

For instance, an increase in capacitance may cause the voltage near the trailing edge of the constant current pulse to increase without any corresponding increase in stimulating strength. This in turn may cause increased energy to be delivered during the pulse, and thus a higher battery energy drain. In the case of a voltage pulse, a decrease in resistance

may cause an increase in current at the leading edge of the pulse and attendant increased battery energy drain. Thus, the battery energy drain is limited in accordance with the invention by limiting the current and/or voltage during the stimulating pulse.

In a voltage pulse, which is typically generated by charging capacitor 28 to a peak value and turning on switch 32 to its maximum conductance, the initial peak current drain is only limited by switch conductance in series with the conductance of the lead system conductors 14.

I/V circuit 20 is capable of limiting high battery energy drain due to shifts in impedance. The closure of output switch 32 is controlled by sensor/controller unit 34. In the preferred embodiment, sensor/controller unit 34 provides a novel feature of sensing both the voltage across and the current through switch 32. Instructions on the shape and duration of the stimulating waveform are received from control circuit 24. The feedback controller in, sensor/controller unit 34 compares the actual current 341 and/or voltage 342 of switch 32 to the wave shape instructions of control circuit 24. Based on the difference of these two signals, control circuit 24 produces an error signal to control switch 32 through negative feedback. These operations can be accomplished in either a digital or analog mode or in a combination thereof. The switch 32 is typically an analog device, and therefore signal 343, which is ultimately produced to control switch 32, may also be analog. The digital portion of this function could be accomplished in control circuit 24 with real-time digitized current and/or voltage data 261 supplied by sensor/controller unit 34.

Another feature of switch 32 working in conjunction with control circuit 24 is the ability to detect when the pulse waveform meets or exceeds a certain limit, or threshold, in voltage; and/or current, to flag that occurrence as an "event," and to log or store the event at the time in which it occurred. This event marker, along with the time during the waveform, is available to control circuit 24 via line 261. Control circuit 24 may also be programmed to detect when the limit, or threshold, is reached during a particular part of the stimulating pulse, i.e., leading edge, trailing edge, etc.

Another feature in accordance with the present invention embodied in I/V circuit 20 is improved accuracy in the operation of voltage multiplier 26. An important novel feature is the added programmable parameter of a voltage and/or current limit or threshold value set by the clinician, in conjunction with the programmable value of either current or voltage, including the shape of the stimulating pulse (e.g., starting current and/or voltage, ending current and/or voltage, start time, stop time, duration, etc.)

The programmable current or voltage threshold parameter is stored with other programmable information in control circuit 24. An instruction based on this, parameter is supplied to voltage multiplier 26 which is capable of charging capacitor 28 to a large number of voltages closely spaced in value. For example, the voltage multiplier 26 would be instructed by control circuit 24 to charge capacitor 28 to a voltage just slightly larger than the programmable voltage limit or threshold. The voltage multiplier 26 may also be used to control the wave shape in conjunction with sensor/controller unit 34.

The processor in control circuit 24 can adjust the voltage multiplier 26 to a lower voltage to achieve the programmed limiting and thus save battery power. The voltage multiplier 26, which may include a switch capacitor array, may increase or decrease the battery voltage V , e.g., in integer or half integer multiples thereof, such as $\frac{1}{2} V_B$, $\frac{3}{2} V_B$, $2 V_B$, 3

V_B , etc. Alternatively, voltage multiplier **26** may be or may contain a transformer, usually in flyback mode, to change battery voltage V_B in order to maintain the necessary voltage, e.g., such that $V_m > I_{program} * R_{electrode}$.

The embodiment of I/V circuit **20** allows for many programmable modes of operation including the modes of constant current and voltage discharge with switch **32** turned on to maximum conductance. One of the additional modes includes a constant current or a controlled-current wave shape with a separately programmable voltage limit or threshold. In this mode, the sensed current **341** may be used to regulate switch **32** through negative feedback. For example, the sensed voltage **342** is compared to the programmable voltage limit. If this sensed voltage **342** reaches this programmable voltage limit, the feedback may be modified to maintain the sensed voltage **342** at this limit. It is understood that the feedback may maintain the voltage at the limit, slightly below the limit, or prevent the voltage from exceeding the limit, as deemed appropriate by one skilled in the art. Another mode of operation is a constant voltage or controlled-voltage wave shape with a separately programmable current limit. In this mode, the sensed voltage **342** may be used to regulate switch **32** with negative feedback. The sensed current **341** is compared to the programmable current limit. If this sensed current **341** reaches the limit, the feedback may be modified to maintain current at this limit. Typically, the initial voltage on capacitor **28** may be set by control circuit **24** to be the minimum voltage required. For instance, if the constant current pulse is programmed to 10 milliamps and the greatest total impedance is 700 ohms, the initial voltage of capacitor **28** would be set at a voltage slightly above seven volts such that the voltage across capacitor **28** at the end of the pulse would be seven volts.

Certain modes of operation in accordance with the invention may not require the use of particular elements described in I/V circuit **20** with respect to FIG. **2**. For example, in the case of constant current or a current-controlled wave shape, voltage limiting may also be achieved without voltage sensing means in control circuit **24** by charging capacitor **28** to the programmed voltage limit value. A limitation in voltage is achieved since the voltage across **28** is theoretically the maximum voltage that can appear across output **14**. In this case, event detection (as described above) can be implemented by detecting saturation or the condition of maximum conductance of switch **32**. In the case of voltage discharge with switch **32** turned on to maximum conductance, no voltage regulation is taking place and therefore the voltage, sensing of **24** is not necessary. However, current sensing is implemented to limit current in this case.

Another feature of the preferred embodiment of I/V circuit **20** is the ability of a stored program or subroutine in control circuit **24** to generate a sequence of current-controlled (and/or voltage-controlled) pulses associated with a sequence of voltage (and/or current) limit values, to interpret resulting limit event data, and to thereby measure the induced voltage (and/or current) waveform shape. The I/V circuit **20** may store this shape for subsequent telemetry to the clinician, and analyze the shape to calculate impedance values, including resistance and/or capacitance components, as will be described in greater detail hereinbelow.

An additional aspect in accordance with the invention is the minimum energy capacity of battery **22**. To achieve long term therapy, e.g., for a three to five year period, the energy limiting features described above are preferably combined

with at least a 10 watt-hr total battery capacity. In the case of lithium type batteries the corresponding total deliverable current should preferably be three ampere hours.

The operation of I/V circuit **20** is described with respect to FIGS. **4**, **5**, and **6(a)–6(c)**. FIG. **4** illustrates a method for setting the values of the upper limit voltage V_{max} . As a result of performing the steps of FIG. **4**, a data table associating current values with upper voltage limits or thresholds V_{max} is compiled. The real-time clock is programmed to apply controlled-current values to the tissue at particular times during the treatment period. Upon implantation of the stimulator, the voltage for each programmed current value may be measured, and a voltage limit may be set for each current value. At step **50**, an initial test voltage limit is set, i.e., V_{lim} . The current-controlled or constant current pulse is applied at step **52**. If the voltage is found to meet or exceed V_{Lim} , at step **54**, the process proceeds to step **56**. V_{max} may be set equal to V_{lim} . Alternatively, V_{max} is calculated as a value greater than the measured V_{lim} , e.g., 125% to 150% of the measured value. The calculated value of V_{max} is stored, preferably in tabular form along with the associated current value, at step **56**. If the voltage does not meet or exceed the present value of V_{lim} , at step **54**, then V_{lim} is reduced by a predetermined increment at step **58**, and the process is repeated until the voltage exceeds the value of V_{lim} . This process is repeated for each current-controlled pulse value until all applicable values of V_{max} are calculated and stored in a table. Alternatively, this process may be carried out for a voltage-controlled pulse in order to create a table of associated current limits. In such a case, an initial value of a test current limit would be set at step **50**, and the voltage-controlled pulse applied at step **52**. The sensed current would be compared with the test current limit at step **54**. If the sensed current is found to meet or exceed the test current limit, a current limit may be set at step **56**. If the sensed current does not meet or exceed the test current limit, the test current limit may be lowered at step **58**, and the process of steps **52–58** repeated. This procedure for setting a table of current/voltage limits is exemplary only, and it is contemplated that other test procedures may be implemented.

FIG. **5**, in conjunction with FIGS. **6(a)–6(c)**, illustrates the operation of the I/V circuit **20** in accordance with the invention during the application of a stimulation waveform to the tissue. The following exemplary procedure is described with respect to a current-controlled pulse with a programmed voltage threshold, but a similar procedure would be carried out for a voltage-controlled pulse with a current threshold.

At step **60**, the current-controlled pulse may be applied to the stomach tissue. The sequencing of various electrical pulses is controlled by the control circuit **24**, described above with respect to FIG. **2**. As illustrated in a time plot in FIG. **6(a)**, the exemplary current pulse commences at t_1 and ends at t_2 . (The durations of the various signals are not shown to scale and may have whatever duration is deemed appropriate to one skilled in the art.) Current-control switch **32** maintains current at the programmed current **64**.

At step **62**, a value is set for an upper voltage limit, i.e., V_{max} . The value of V_{max} may be fixed. Alternatively, V_{max} may be adjustable or programmable based on the circuit operating conditions, such as, for example, the magnitude of the current applied at step **60**. A lookup of the tabular data compiled in FIG. **4** may be performed to set a value of V_{max} .

At step **66**, the sensor/controller unit **34** measures sensed voltage and determines whether the voltage meets or exceeds the upper voltage limit V_{max} . The sensor/controller

unit **34** may be programmed to measure continuously or periodically store voltage data telemetry at step **66**. A time plot illustrating voltage V across the tissue is shown at FIG. **6(b)**. Due to the polarization capacitance effect of the stomach tissue, the voltage across the stomach tissue increases as the circuits attempts to maintain constant current. Thus, the voltage, initially at voltage **68** at t_1 , may increase to voltage **70** at t_2 . (FIGS. **6(a)**–**6(c)** are aligned such that signals represented in the FIGS. in the same horizontal position occur simultaneously.) In FIG. **6(b)**, the voltage meets or exceeds voltage limit V_{max} **72** at t_3 .

The comparison of the voltage with the voltage limit V_{max} (step **66**) may occur continuously during the stimulating pulse. Alternatively, the voltage sensor **34** may be programmed to compare the voltage with the voltage limit V_{max} at the leading edge of the stimulating pulse, i.e., at a time period near t_1 . According to another alternative embodiment, the voltage sensor **34** may be programmed to determine if the voltage meets or exceeds V_{max} at the trailing edge of the stimulating pulse, i.e., at a time period near t_2 .

If the voltage limit sensor **34** is not triggered, i.e., voltage is below voltage limit V_{max} , operation of the circuit proceeds on path **74** of the flowchart of FIG. **5**, and the circuit applies a current pulse to the tissue, as required by the control circuit. Voltage limit V_{max} may be set to a new value at step **62** if operating conditions require, e.g., if the current pulse changes.

However, if the voltage meets or exceeds voltage limit V_{max} , several operating steps may also occur. Steps **76**, **78**, **80**, and **82** are illustrated in sequential order. However, it is understood that steps **76**, **78**, **80**, and **82** are independent and may occur in a different order or simultaneously, as deemed appropriate by one skilled in the art. Certain ones of these steps may also be omitted, if desired to change the functionality of the circuit.

At step **76**, the occurrence of the “event” described above, i.e., the occurrence of voltage meeting or exceeding the upper voltage limit V_{max} is stored, e.g., in the memory of the control circuit. In the example of FIG. **6(b)**, the event occurred at time t_3 . The time associated with the event may be measured as an absolute time value, i.e., the calendar date and time, or as the elapsed time from the initiation of the treatment, or as the elapsed time from the initiation of the particular current pulse. The occurrence of the event may be included in telemetry data, as with the voltage data at step **66**, above. The event data point may include the current value and the voltage at the, time the event occurred, i.e., a “current value- voltage limit pair.”

With continued reference to FIG. **5**, data may be calculated at step **78**. For example, the total lead resistance R_{off} may be calculated, for example, as the ratio of V_{max} divided by the programmed current (I_{prog}). The event datapoint may also include associating the current value with the electrode lead resistance, i.e., as an “electrode resistance pair.” This data point may also be stored in the telemetry data. Monitoring lead resistance is useful in predicting the battery life of the stimulator. As described above, increased resistance causes a substantial voltage drain on the; battery, with associated reduction in battery life.

The polarization capacitance may also be calculated from the data taken during the above-steps. For example, the polarization capacitance may be calculated as the ratio of the programmed current to the time rate of change of the voltage (i.e., $C_{polarization} = I_{prog}/dV/dt$). From the parameters being measured, the time rate of change of the voltage may be

approximated from the change in voltage between the voltage **68** at the leading edge t_1 and the voltage **70** at the trailing edge t_2 of the pulse and the time elapsed during the pulse, or the pulsewidth (i.e., t_2-t_1). Calculation of the polarization capacitance provides information on battery drain, wherein a large capacitance may be indicative of high drain on the battery that reduces battery life. The event data point may also include associating the current value with the polarization capacitance. This data point may also be stored in the telemetry data.

At step **80**, voltage may be adjusted by using the voltage multiplier **26**. For example, the control circuit **24** may be programmed to adjust the voltage multiplier **26** to reduce voltage in integer or fractional integer increments. With reference to FIG. **6(c)**, after the event occurs at t_3 , the voltage is adjusted to remain at the level of voltage limit V_{max} **72**, slightly below voltage limit V_{max} **72**, or not to exceed V_{max} **72**.

The calculation of lead resistance and polarization capacitance at step **78** may be helpful in determining the degree of voltage adjustment in order to maintain the voltage below V_{max} . A large value of electrode resistance or polarization capacitance may indicate a substantial drain on the battery. Accordingly, a substantial adjustment may be made in the voltage at step **80**. Conversely, smaller values of electrode resistance or polarization capacitance may indicate a less substantial drain on the battery, and a smaller adjustment to keep the voltage a or below V_{max} .

At step **82**, the event data stored or calculated at steps **76**–**80** may be graphically displayed or listed on a display terminal or printed output. The process may continue until it is determined that the, treatment is completed at step **84**, at which time the current/voltage limitation may be ended (step **86**).

As illustrated in FIG. **3**, above, I/V Circuit **20** includes a real-time clock **46**, which supplies data corresponding to the time of day during the treatment period, and programmable calendar **48**, that can be programmed to store the parameters that define the above pulse train. The parameters are used by the control circuit **24** in determining the wave shape of the stimulating pulse. The parameters correspond to particular times during the treatment. Medical observations suggest that food intake, digestion and other gastrointestinal functions are circadian, that is, they operate on a 24 hour daily cycle. There are certain periods during the day when gastric functions are less active than other times of the day. The programmable calendar **48** can therefore provide increased stimulation at certain hours of the day, and decreased stimulation at other hours of the day. Among other benefits, device longevity may be increased due to the energy saving of this programming. Thus the stimulators **12** may deliver stimulation pulses for a fraction of each hour while the patient is awake. The programmability of calendar **48**, described below, allows the application of longer-term circadian variations which may likewise be beneficial to the patient and extend battery life.

A plurality of pulse train parameters may be stored in memory associated with the programmable calendar **48**. Sample data **90** for a treatment period is shown in FIG. **7**. The data **90** may be for a 24-hour period, such as “day one” **92**, which may include calendar information **94**. The pulse trains may be stored as cycles **96**. For example, pulse train parameters may include start times **98**, stop times **100**, the pulsewidth **102**, the pulse interval **104**, the duration of the applied pulses (the “on” period) **106**, or the duration period

in which no pulses are applied (the “off” period) **108**, and the voltage of the pulse or the pulse height **109**. The programmable calendar **48** receives data from the clock **46** concerning the time-of-day and the date. Programmable calendar **48** can obtain the associated parameters from the data **90** and supply them the processor **44**, accordingly. The “date” associated with the treatment may vary, depending on the expected duration of the treatment. For example, in data format **110** (FIG. **8**), the data may correspond to the day of week (e.g., “day one” **112** through “day, seven” **114**). Each of the data points in day one **112** through day seven is similar to data point **90**. The programmable calendar **48** may function on a seven-day cycle wherein programmable calendar accesses day one after day seven in a continuous loop **116**. Thus, each day of the week could have a particular sequence of stimulating pulse train parameters. As a result, the pulse train is programmed to stimulate the stomach tissue in the same way on the same day of each week.

As illustrated in FIG. **9**, the data format **120** may refer to a simple, numbered day in a periodic sequence of days, such as the numbered days of the year (i.e., “day one” **122** through day **365**” **124**), or the numbered days within a month (e.g., “day one” **112** through “day **31**”, not shown). The calendar **48** would then cycle back to the first data point as indicated by arrow **126**. As illustrated in FIG. **10**, the data format **130** may be hierarchical and thus may recognize intermediate time periods, such as weeks **132** and/or months (not shown) within a treatment period. For example, it may recognize that the treatment is at “week two” **134** or “week three” **136**, in addition to the elapsed number of days. The calendar **48** could be programmed to so that the pulse generator **10** is turned off for a number of weeks. The generator may then be turned on one day a week, During the next week, the generator may be turned on for two days a week, etc. Each sequence of cycles (see, FIG. **7**) within a given “on” day, could also be different from the previous “on” day.

The programmability of the pulse train wave forms based on the date provides the ability to turn the above stimulating pulse train on or off or increase or decrease waveform parameters over increasingly longer meshed periods of time.

An alternative embodiment of the neuromuscular stimulator described above includes an additional mode for stimulating the neuromuscular tissue of the gastrointestinal tract. The neuromuscular stimulator applies a series of primary electrical pulses to the tissue as described hereinabove. These electrical pulses may be applied during a first time interval, and may be discontinued during a second time interval. A secondary series of pulses having a lower voltage may be applied to the tissue during the second time interval, i.e., when the primary electrical pulses are discontinued. The resulting current flowing between the stimulating electrode pair is measured.

Data, including, for example, sensed current, may be measured. The current data may be analyzed for changes over time. From this analysis, statistics may be computed. For example, a statistic which may be computed is the time period in which the changes in the current data repeats. This time period may be used to approximate the peristaltic action of the tissue. It may be desirable to change the rate of peristaltic activity, i.e., to slow down or increase the rate thereof, by varying the series of electrical pulses based on the statistics as described above.

The foregoing is merely illustrative of the principles of this invention and various modifications can be made by those skilled in the art without departing from the scope and spirit of the invention.

What is claimed is:

1. A neuromuscular stimulator for stimulating tissue of the gastrointestinal tract by applying a current-controlled electrical pulse to the neuromuscular tissue, comprising:

a voltage sensor to detect a voltage across the neuromuscular tissue being stimulated; and

circuitry configured to (a) compare the voltage with a predetermined voltage threshold and to adjust the current-controlled pulse if the voltage is found to meet the predetermined voltage threshold, such that the voltage does not exceed the predetermined voltage threshold, (b) calculate electrode resistance; said electrode resistance being voltage limit value divided by current value and (c) determine an increment of adjustment of voltage based on the electrode resistance.

2. The neuromuscular stimulator defined in claim **1**, wherein the voltage threshold is adjustable.

3. The neuromuscular stimulator defined in claim **1**, wherein the circuitry is configured to set the voltage threshold based on a current level associated with the current-controlled pulse.

4. The neuromuscular stimulator defined in claim **3**, wherein the circuitry is configured to prepare a set of voltage thresholds and associated respective current levels.

5. The neuromuscular stimulator defined in claim **1**, wherein the circuitry is configured to associate the electrode resistance with the current level of the current-controlled pulse.

6. The neuromuscular stimulator defined in claim **5**, further comprising:

a memory device to store the electrode resistance and the associated current level.

7. The neuromuscular stimulator defined in claim **1**, further comprising:

a display device to display the electrode resistance and the associated current level.

8. The neuromuscular stimulator defined in claim **1**, further comprising:

a memory device to store an event characterized by the voltage being found to meet the predetermined voltage threshold.

9. The neuromuscular stimulator defined in claim **1**, wherein the voltage sensor is configured to detect the voltage across the neuromuscular tissue at a leading edge of the electrical pulse.

10. The neuromuscular stimulator defined in claim **1**, wherein the voltage sensor is configured to detect the voltage across the neuromuscular tissue at a trailing edge of the electrical pulse.

11. A neuromuscular stimulator for stimulating tissue of the gastrointestinal tract by applying a current-controlled electrical pulse to the neuromuscular tissue comprising:

a voltage sensor to detect a voltage across the neuromuscular tissue being stimulated; and circuitry configured to (a) compare the voltage with a predetermined voltage threshold and to adjust the current-controlled pulse if the voltage is found to meet the predetermined voltage threshold such that the voltage does not exceed the predetermined voltage threshold and (b) calculate capacitance of said tissue, said capacitance being the ratio of the current and the time rate of change of the voltage during an individual electrical stimulating pulse.

12. The neuromuscular stimulator defined in claim **11**, wherein the circuitry is configured to determine the increment of adjustment based on the capacitance.

13

13. The neuromuscular stimulator defined in claim 11, wherein the circuitry is configured to associate the capacitance with the current level of the current-controlled pulse.

14. The neuromuscular stimulator defined in claim 11, further comprising:

a memory device to store the capacitance and the associated current level.

15. The neuromuscular stimulator defined in claim 11, further comprising:

a display device to display the capacitance and the associated current level.

16. A neuromuscular stimulator for stimulating tissue of the gastrointestinal tract by applying a current-controlled electrical pulse to the neuromuscular tissue, comprising:

a voltage sensor to detect a voltage across the neuromuscular tissue being stimulated; and

circuitry configured to compare the voltage with a predetermined voltage threshold and to adjust the current-controlled pulse if the voltage is found to meet the predetermined voltage threshold such that the voltage does not exceed the predetermined voltage threshold.

wherein the neuromuscular stimulator is configured to determine and store a time value during the electrical pulse when the voltage associated with the electrical pulse meets the predetermined voltage threshold.

17. A method of stimulating neuromuscular tissue of the gastrointestinal tract comprising:

(a) preparing a set of voltage thresholds and associated respective current levels comprising:

setting a test value for the voltage threshold;

applying a first current pulse to the tissue to be stimulated;

iteratively varying the test value until the voltage level across the tissue is found to meet the test value; and

associating the voltage level with the respective current level in the set of voltage thresholds;

(b) applying a current-controlled electrical pulse to the neuromuscular tissue to stimulate the neuromuscular tissue;

(c) detecting a voltage across the neuromuscular tissue being stimulated;

setting the voltage threshold based on a current level associated with the current-controlled pulse;

(d) comparing the voltage with a predetermined voltage threshold; and

(e) adjusting the current-controlled pulse if the voltage is found to meet the predetermined voltage threshold by the detecting, such that the voltage does not exceed the predetermined voltage threshold.

18. The method defined in claim 17, wherein preparing the set of voltage thresholds further comprises:

before the step of associating, multiplying the measured voltage level by a factor selected from a range between about 1.0 and 1.5.

19. The method defined in claim 17, wherein the detecting a voltage across the neuromuscular tissue being stimulated comprises detecting the voltage at a leading edge of the electrical pulse.

20. The method defined in claim 17, wherein the detecting the voltage across the neuromuscular tissue being stimulated comprises detecting the voltage at a trailing edge of the electrical pulse.

21. A method of stimulating neuromuscular tissue of the gastrointestinal tract comprising:

(a) applying a current-controlled electrical pulse to the neuromuscular tissue to stimulate the neuromuscular tissue;

14

(b) calculating electrode resistance, said electrode resistance being voltage limit value divided by current value;

(c) detecting a voltage across the neuromuscular tissue being stimulated;

(d) comparing the voltage with a predetermined voltage threshold; and

(e) adjusting the current-controlled pulse if the voltage is found to meet the predetermined voltage threshold by the detecting such that the voltage does not exceed the predetermined voltage threshold wherein the step of adjusting the current-controlled pulse comprises determining an increment of adjustment of voltage based on the electrode resistance.

22. The method defined in claim 21, further comprising: after calculating the electrode resistance, associating the electrode resistance with the current level of the current-controlled pulse.

23. The method defined in claim 22, further comprising: after the step of associating the electrode resistance with the current level of the current-controlled pulse, storing the electrode resistance and the associated current level in a database.

24. The method defined in claim 21, further comprising: after the step of associating the electrode resistance with the current level of the current-controlled pulse, displaying the electrode resistance and the associated current level.

25. A method of stimulating neuromuscular tissue of the gastrointestinal tract comprising:

(a) applying a current-controlled electrical pulse to the neuromuscular tissue to stimulate the neuromuscular tissue;

(b) calculating capacitance of said tissue, said capacitance being the ratio of the current and the time rate of change of the voltage;

(c) detecting a voltage across the neuromuscular tissue being stimulated;

(d) comparing the voltage with a predetermined voltage threshold; and

(e) adjusting the current-controlled pulse if the voltage is found to meet the predetermined voltage threshold by the detecting, such that the voltage does not exceed the predetermined voltage threshold.

26. The method defined in claim 25, wherein the step of adjusting the current-controlled pulse further comprises: determining the increment of adjustment based on the capacitance.

27. The method defined in claim 25, further comprising: after the step of calculating the capacitance, associating the capacitance with the current level of the current-controlled pulse.

28. The method defined in claim 25, further comprising: after the step of associating the capacitance with the current level of the current-controlled pulse, storing the capacitance and the associated current level in a database.

29. The method defined in claim 25, further comprising: after the step of associating the capacitance with the current level of the current-controlled pulse, displaying the capacitance and the associated current level.

30. The method defined in claim 25, wherein the detecting a voltage across the neuromuscular tissue being stimulated comprises detecting the voltage at a leading edge of the electrical pulse.

15

31. The method defined in claim 25, wherein the detecting the voltage across the neuromuscular tissue being stimulated comprises detecting the voltage at a trailing edge of the electrical pulse.

32. A method of stimulating neuromuscular tissue of the gastrointestinal tract comprising: 5

- (a) applying a current-controlled electrical pulse to the neuromuscular tissue to stimulate the neuromuscular tissue;
- (b) detecting a voltage across the neuromuscular tissue being stimulated; 10

16

- (c) comparing the voltage with a predetermined voltage threshold;
- (d) storing an event in memory characterized by the voltage being found to exceed the predetermined voltage threshold; and
- (e) adjusting the current-controlled pulse if the voltage is found to meet the predetermined voltage threshold by the detecting such that the voltage does not exceed the predetermined voltage threshold.

* * * * *